The Atomic, Molecular & Plasma Physics Group
University College Dublin
Speclab

Exploring Radiance

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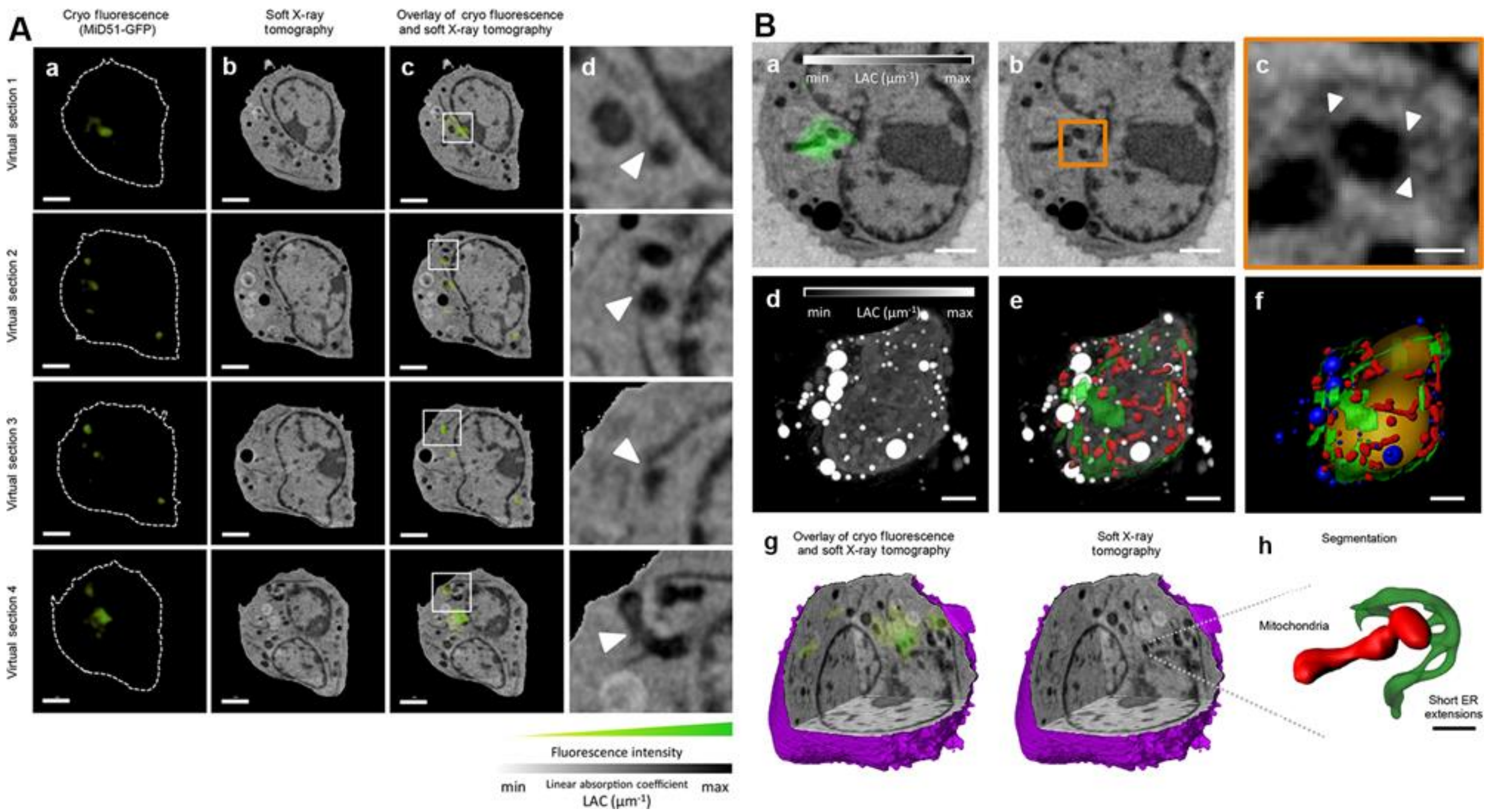
UCD DUBLIN

Soft X-ray Nanoscopy



Soft X-ray Imaging of particular interest if SPATIAL RESOLUTION better than 50 nm

Larabell et al: Biol. Cell (2017) **109,** 24–38 DOI: 10.1111/boc.201600044

Imaging Challenge

CCD Cameras are Soft
X-ray imaging
Gold Standard

Smallest **Pixels > 13 µm**
For 50 nm resolution **object pixels < 15 nm**
(2D Nyquist Resolution)
So **magnification > 1000**

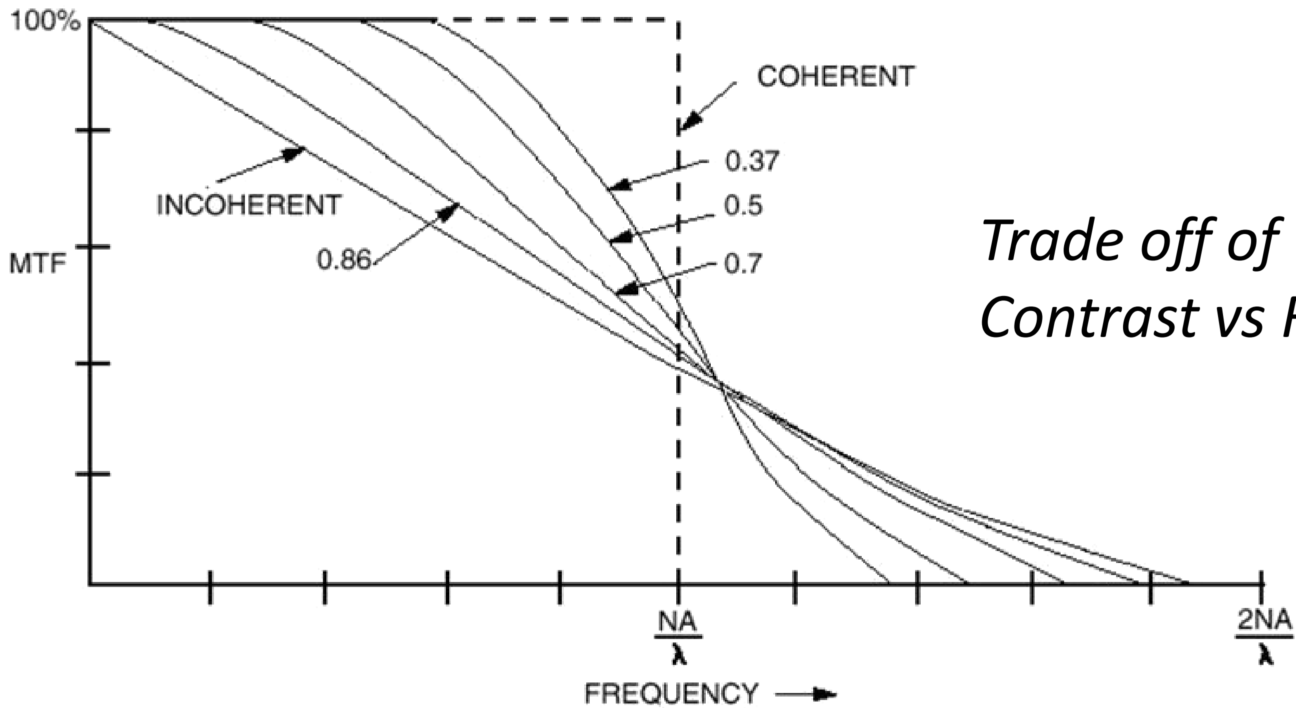
Affordable (< €50k)   CCD has 25 mm X 25 mm size

At > x1000 mag that means **FOV < 25 µm** field of view

Rayleigh Resolution

For 50 nm resolution at 2.5 nm – **NA > 0.03 (> 0.003 steradians)**

Resolution ~ $1.22\lambda/(NA_{illumination} + NA_{objective})$



Trade off of Contrast vs Resolution

Coherence = $NA_{illumination}/NA_{objective}$

Photon Flux

- At Sample:
  - Ideally want >1000 photons/pixel/image
  - This is what the synchrotron systems can achieve
  - Fills the CCD pixel well
  - Gives highest possible contrast

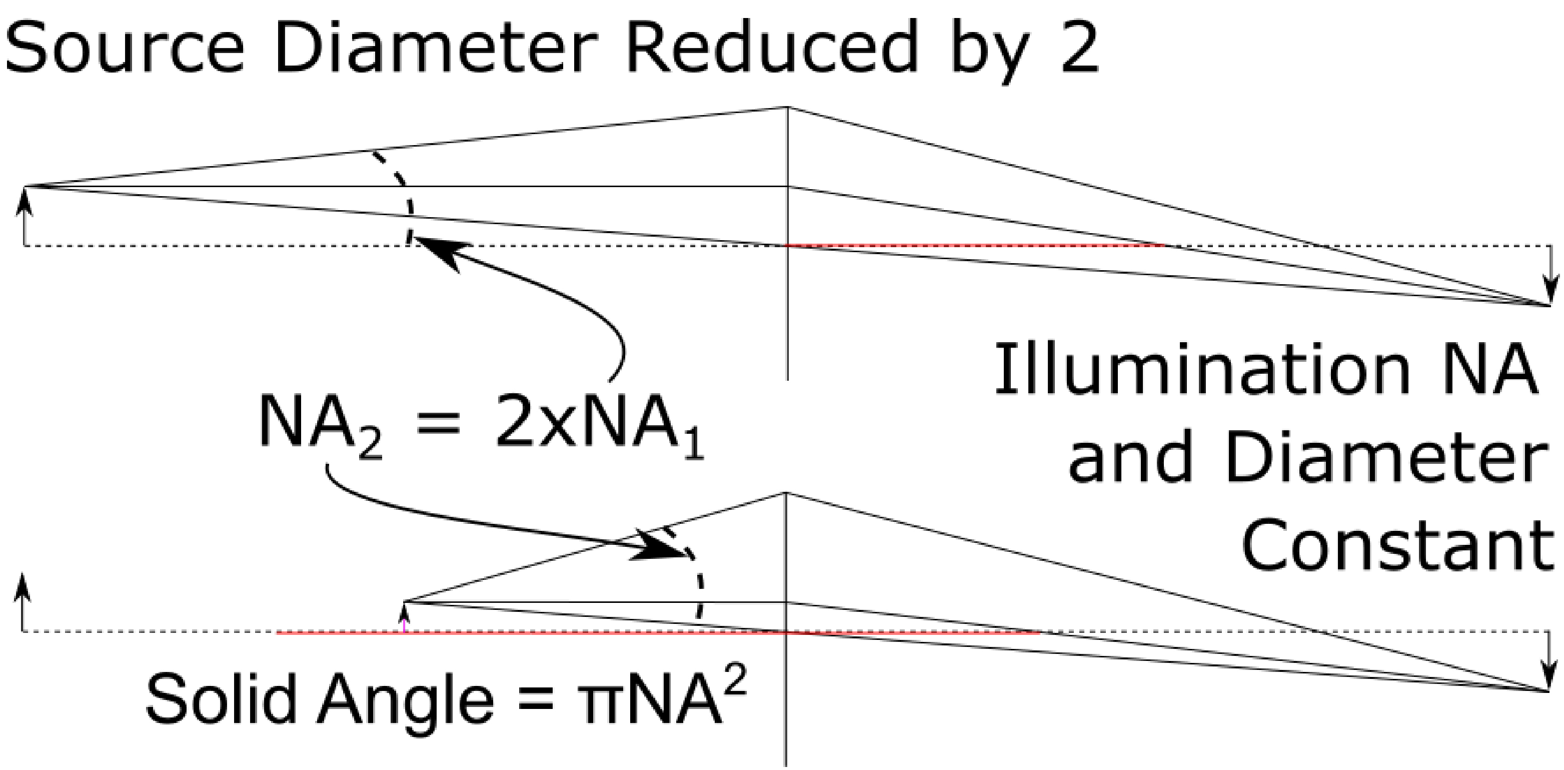
Average Radiance at Sample

- 2D Images taken over second timescales

- $Radiance = \frac{\boldsymbol{SourceFlux} \times SystemTransmission}{(\boldsymbol{FOV\ Diameter^2} \times Objective\ Solid\ Angle)}$

- *Peak radiance is only of interest if you are looking at fast phenomena*

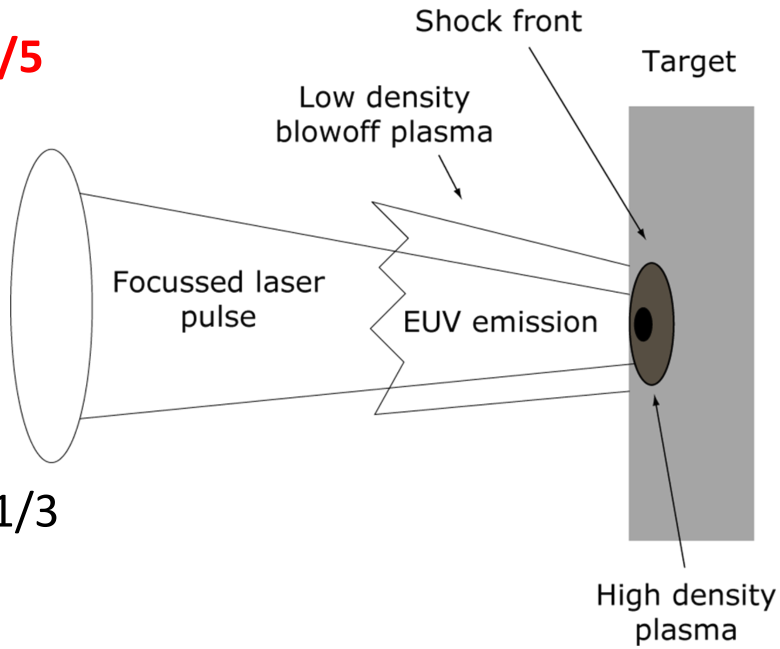
Source Size and Collection



Collect 4x photons from source

Laser Plasmas & Soft X-rays

$T_e(\text{eV}) \approx (\lambda^2$ **PowerDensity**$)^{3/5}$
(Columbant & Tonan, JAP 44 1973)

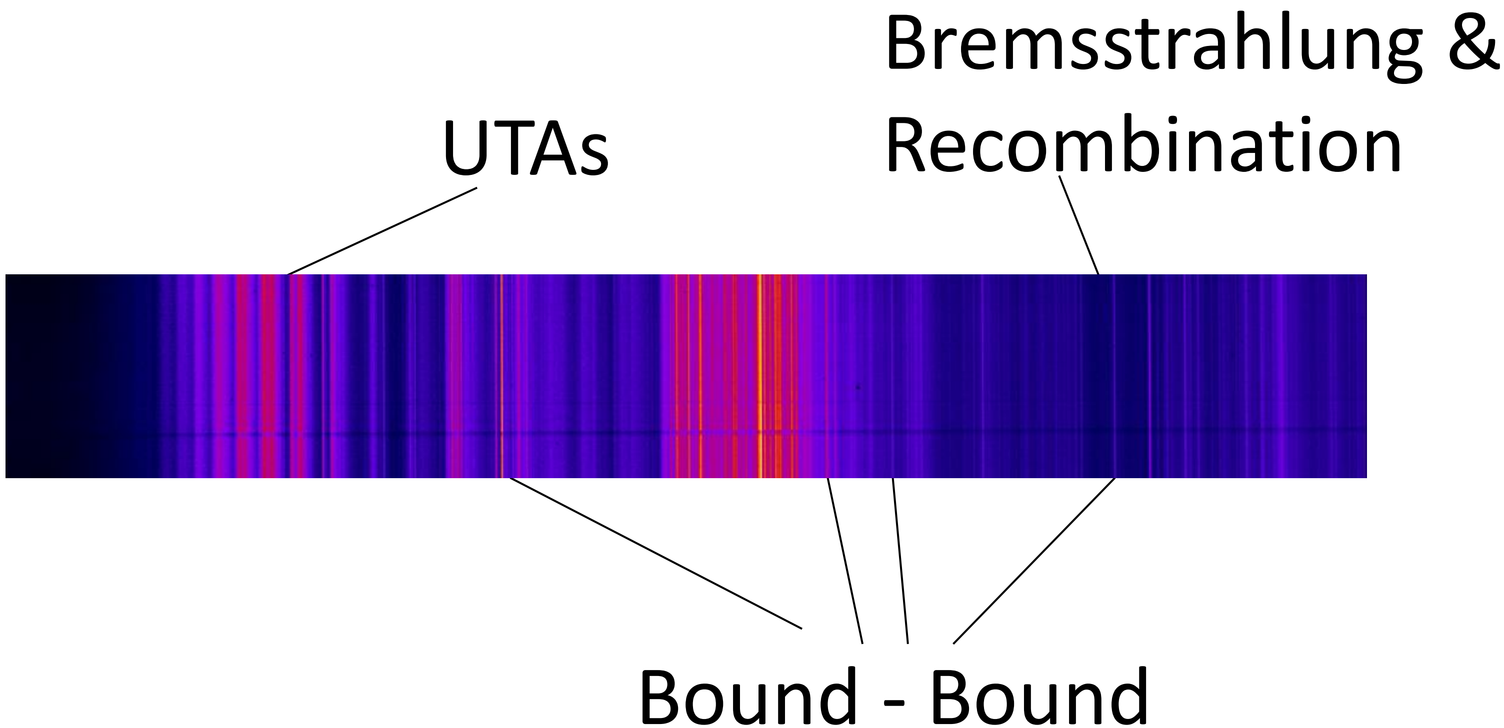


Average charge $\approx 0.67\,(AT_e)^{1/3}$

$n_e \sim 10^{19} - 10^{21}\ \text{cm}^{-3}\ (n_{ec} \sim 10^{21}/\lambda^2\ \text{cm}^{-3})$

Expansion velocity $\approx 10 - 100\ \mu\text{m/ns}$
$(\approx 10^6 - 10^7\ \text{cm/s})$

Soft X-ray/EUV Spectrum



For an optically thin plasma:

$$P_{lines}:P_{recomb}:P_{brem} = 100:10:1$$

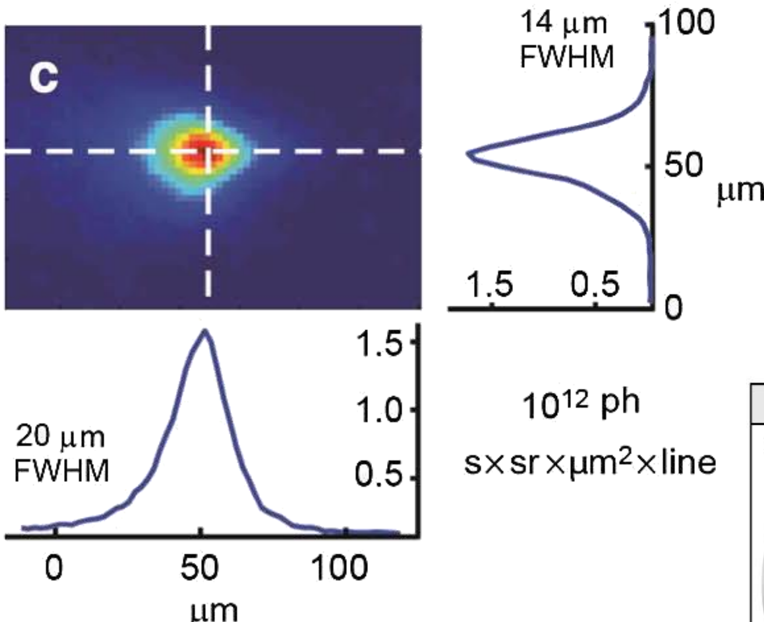
Plasma Size Experiments

- Requirements:
  - to **image plasmas < 5µm**
  - simultaneous Soft X-Ray spectroscopic study

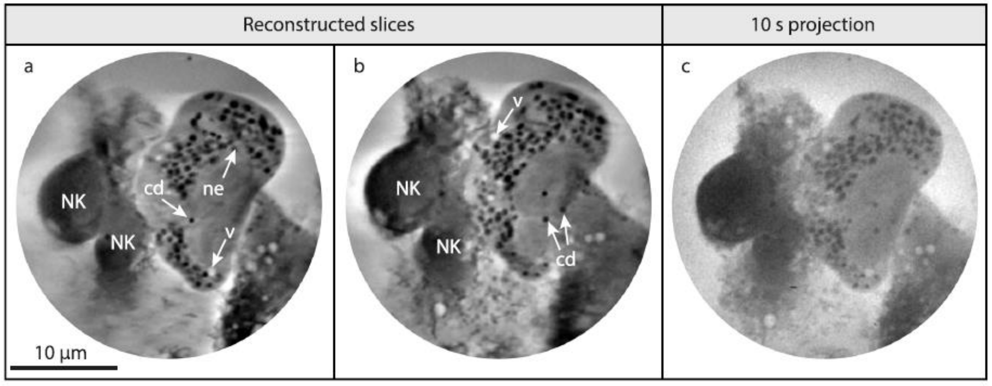
- Objective:
  - Explore the size and shape of the Soft X-Ray plasmas with different target materials
  - Understand the Soft X-Ray emission volume from different materials at different conditions
  - **Optimise Radiance** at particular wavelengths

Current State of the Art

- Hans Hertz ~ 14µm x 20µm – measured with condenser zone plate and multilayer optic



Martz et al November 1, 2012 / Vol. 37, No. 21 / OPTICS LETTERS



Fogelqvist et al, Scientific **Reports** | 7: *13433* | DOI:10.1038/s41598-017-13538-2

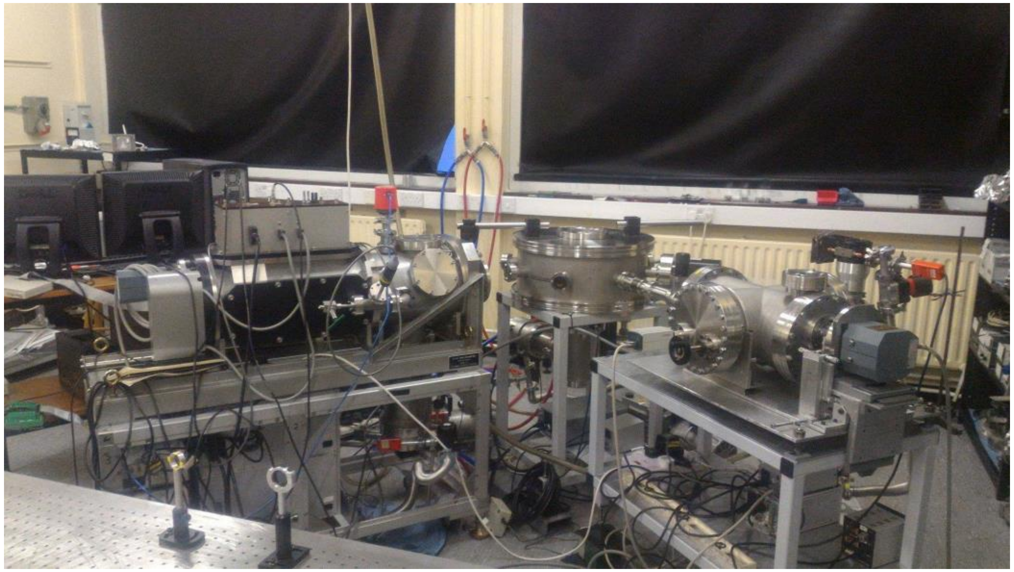
UCD Expertise

- Plasma facing optics
- Can use very high laser illumination NA
- So potentially very small plasmas
- Of potentially any target
- Can use inexpensive industrial lasers

High Resolution Soft X-ray Source Imaging

Facilities at UCD SPEC Lab

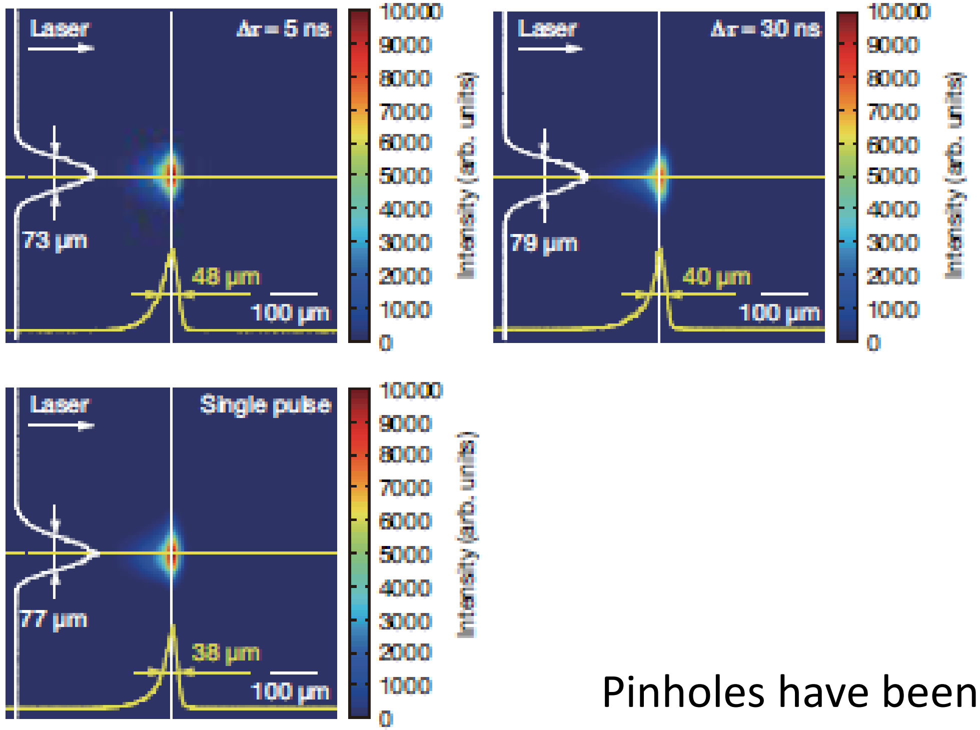
Lasers



Main chamber and Spectrometers

800 mJ, 7 ns, 1064 nm M2 ~3.5
500 mJ, 170 ps, 1064 nm M2 ~5
50 mJ, 20 ps, 1064 nm M2 ~5

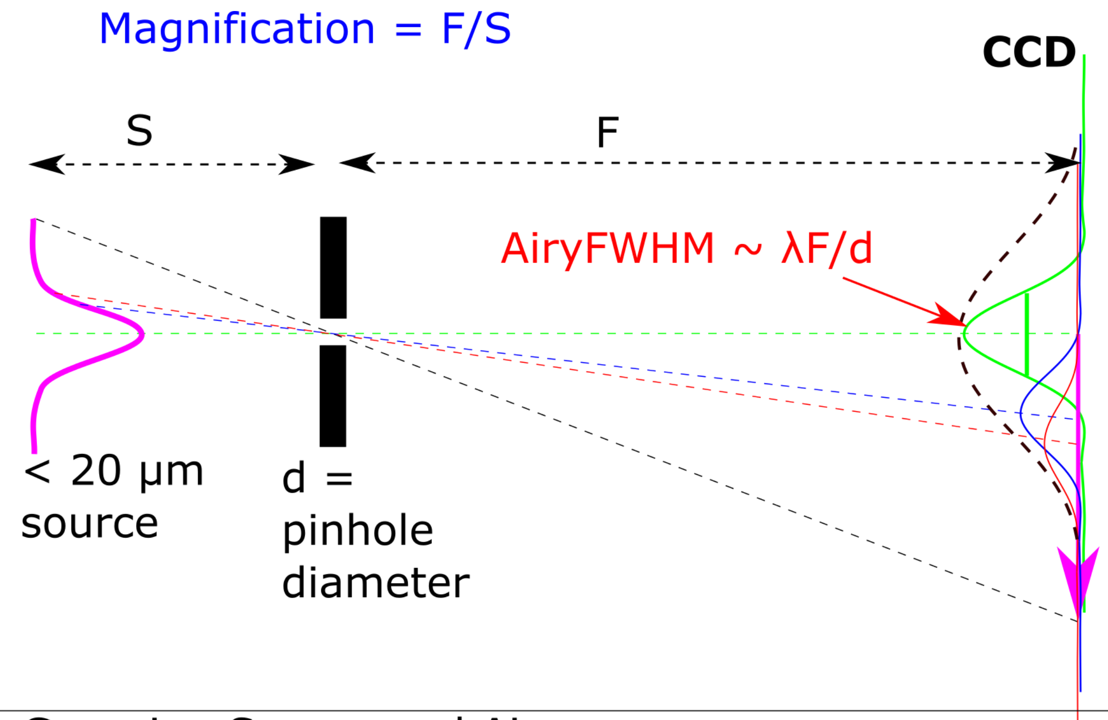
Previous Imaging



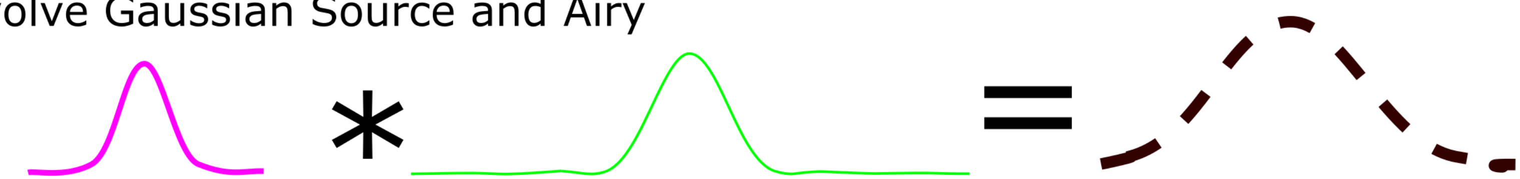
Pinholes have been used before

Miyazaki et al, http://www.euvlitho.com/2015/S53.pdf

Experiment

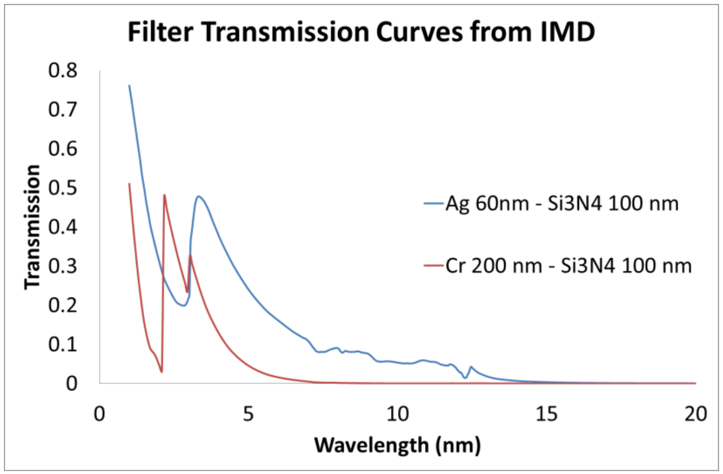


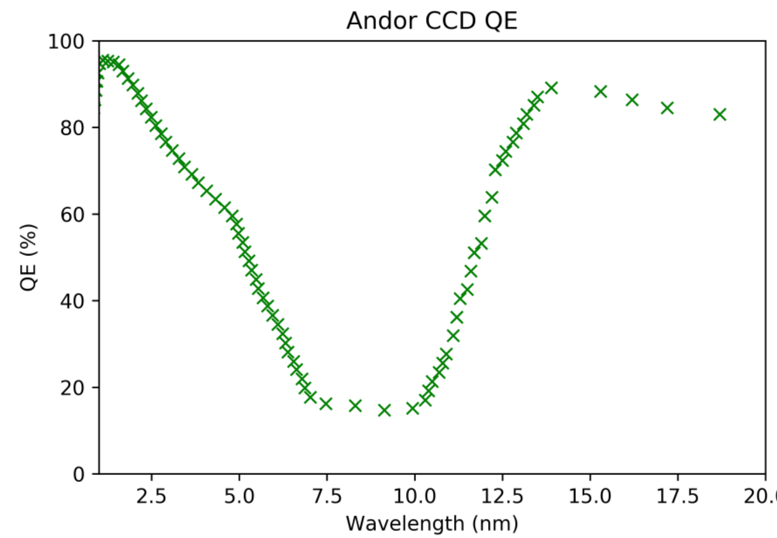
Convolve Gaussian Source and Airy

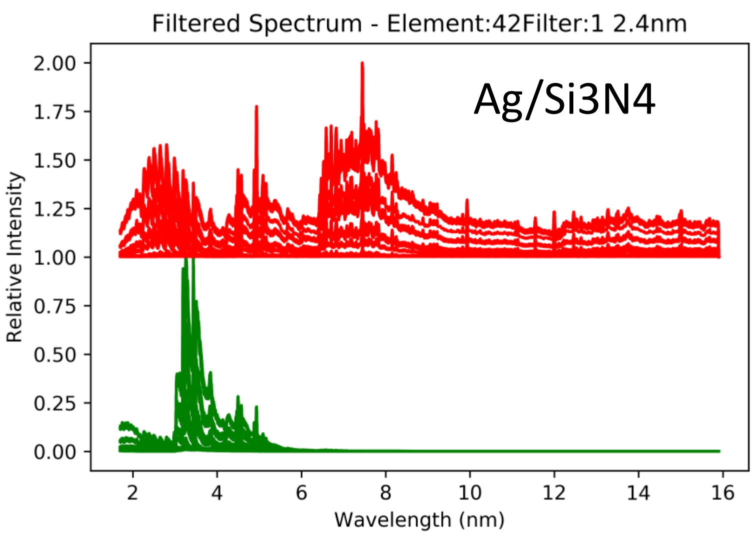


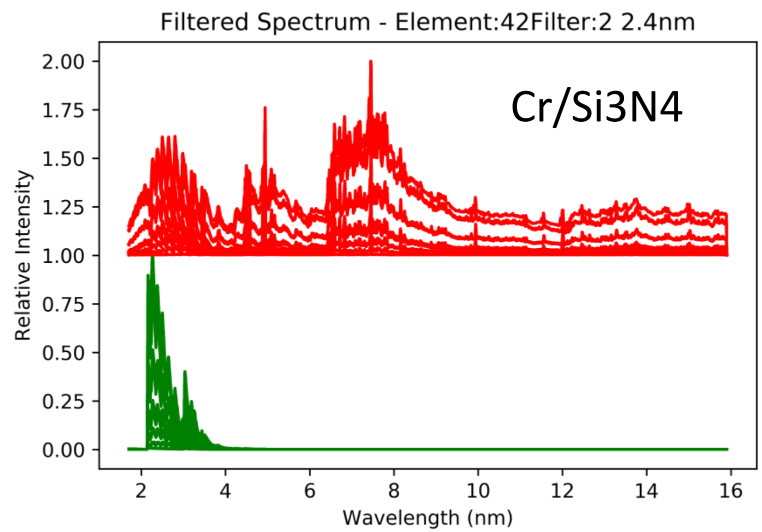
$$(\text{Magnification} * \text{Source FWHM})^2 + \text{Airy FWHM}^2 = \text{Image FWHM}^2$$

Filtered Spectrum

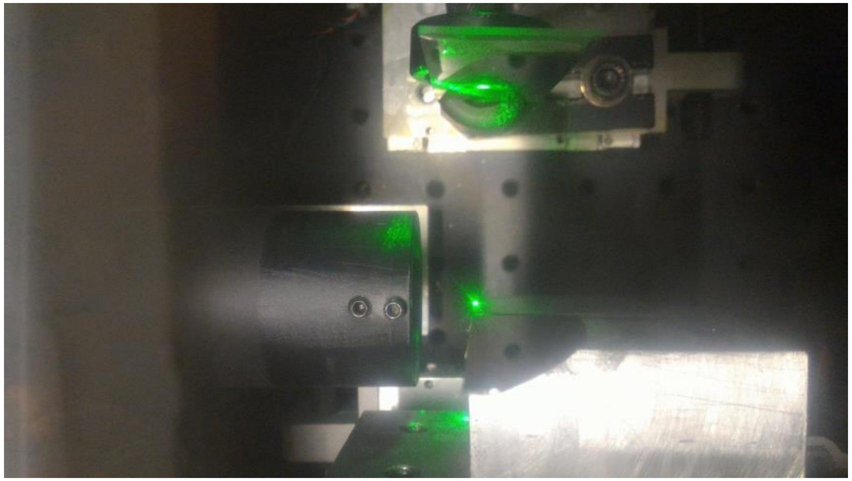




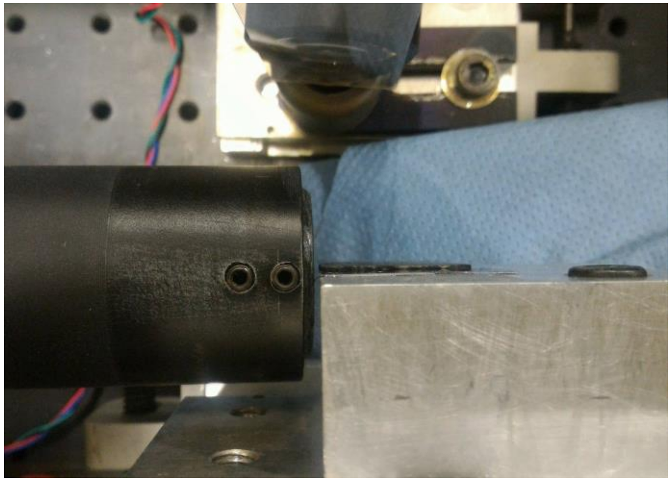




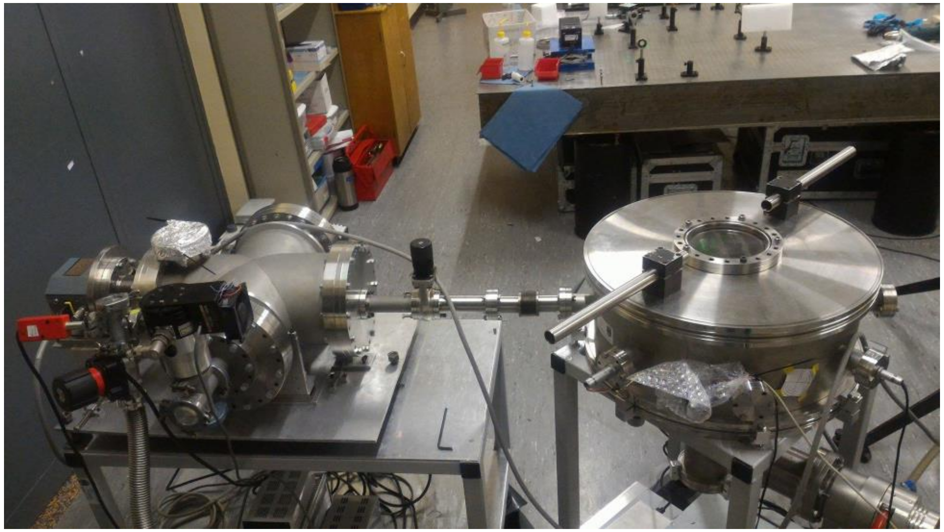
Experiment Setup



Pinhole at lower magnification



Pinhole at higher magnification



Spectroscopy setup

Pinhole Comparison with Mo plasma

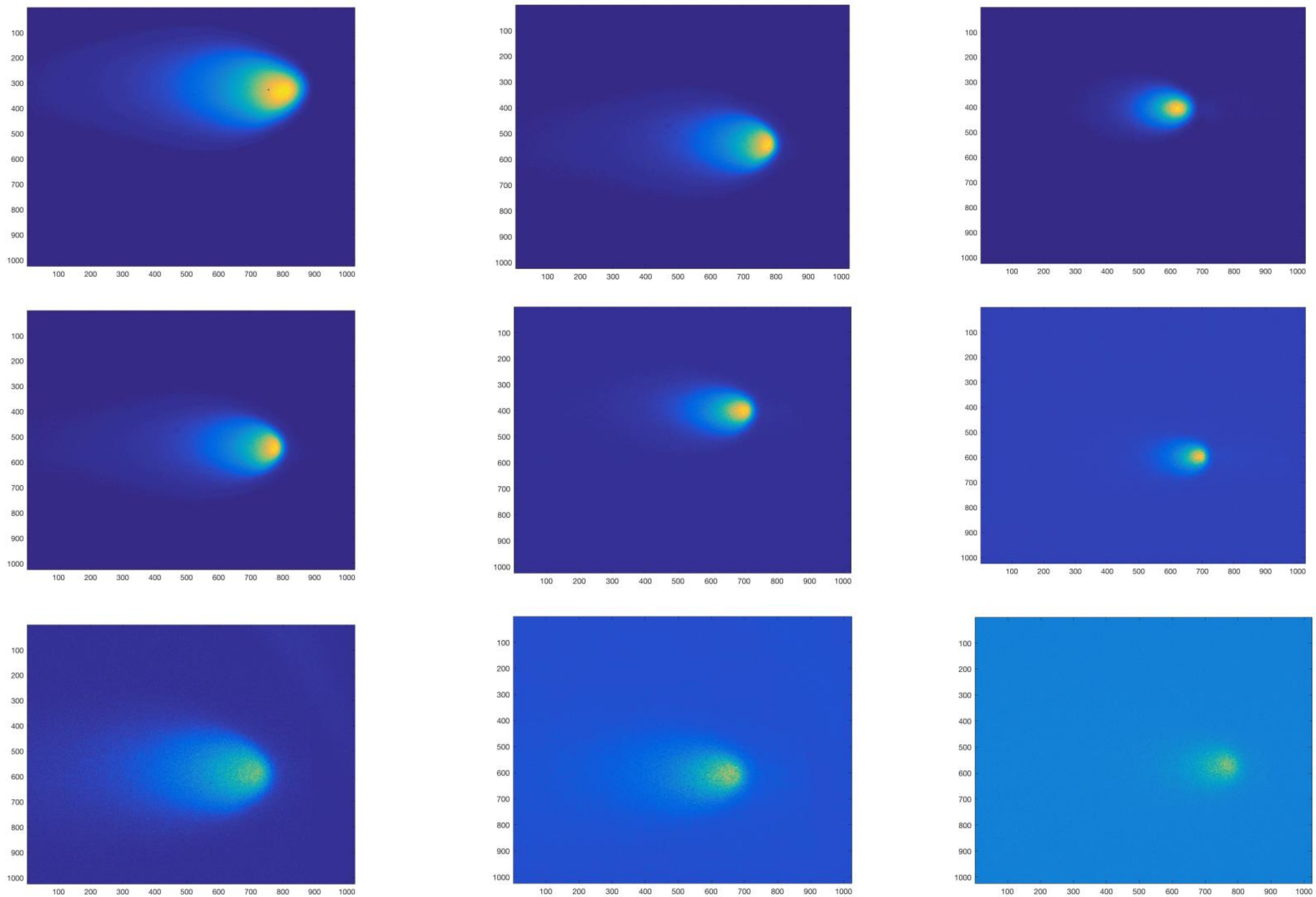
Laser Energy 800mj 200mj 50mj

Pinhole Diameter

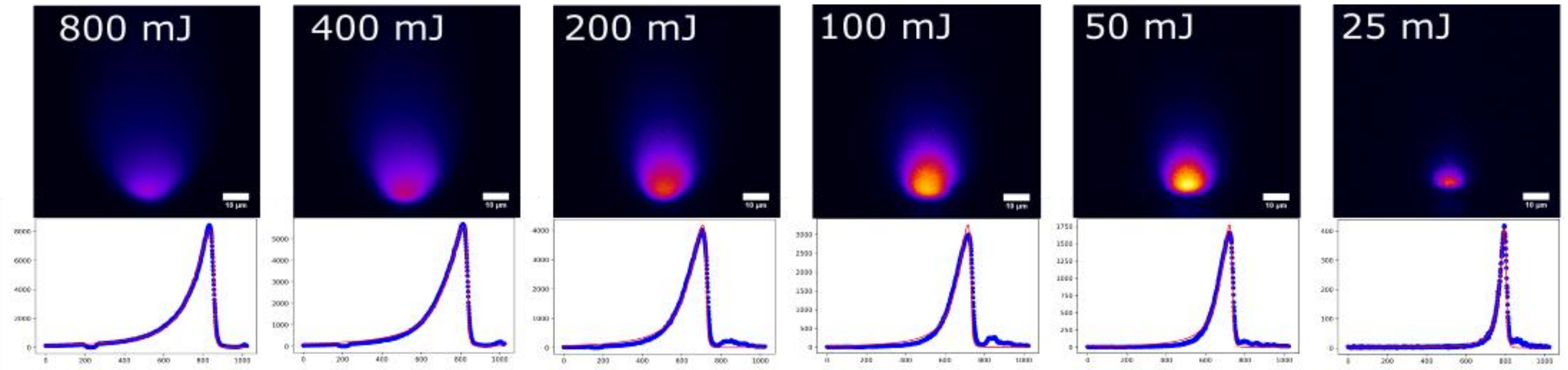
10µm

5µm

2µm



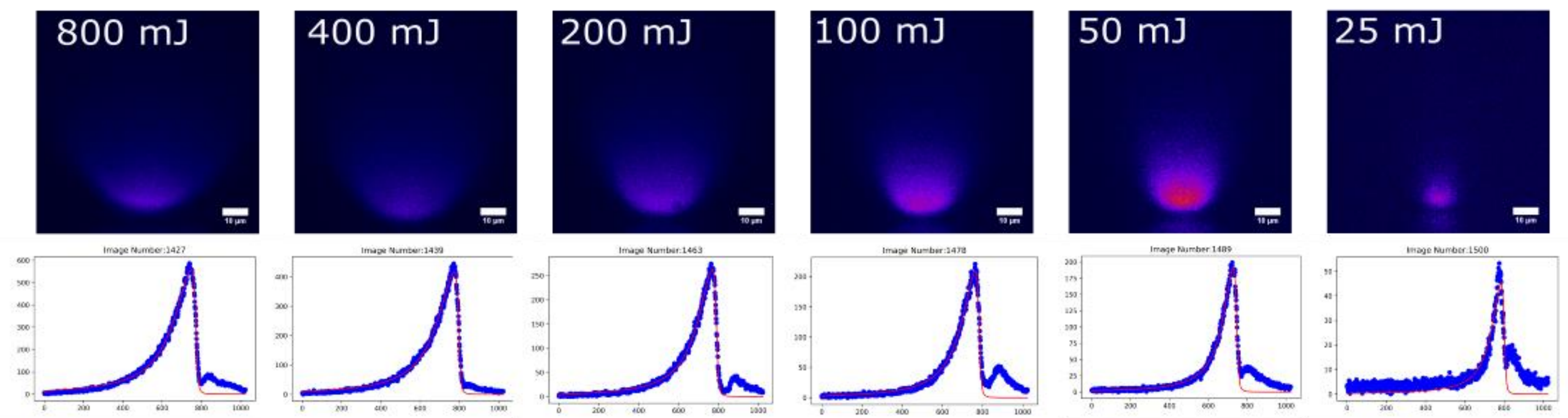
Energy Scan



Molybdenum

Images are Energy Normalised

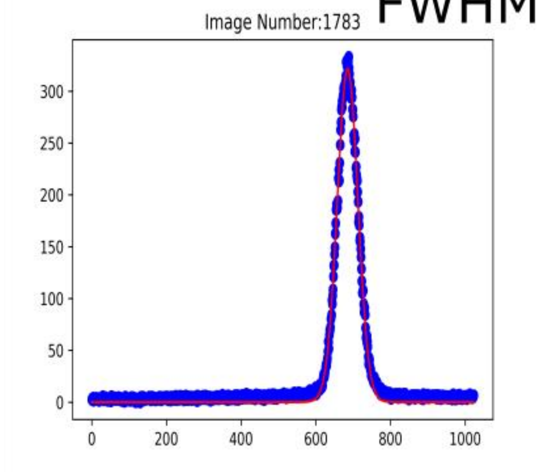
Silicon

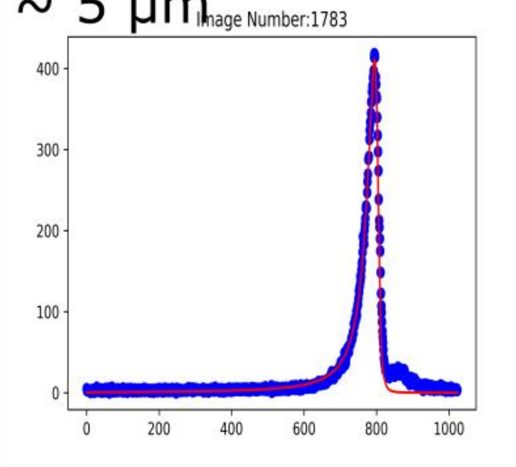


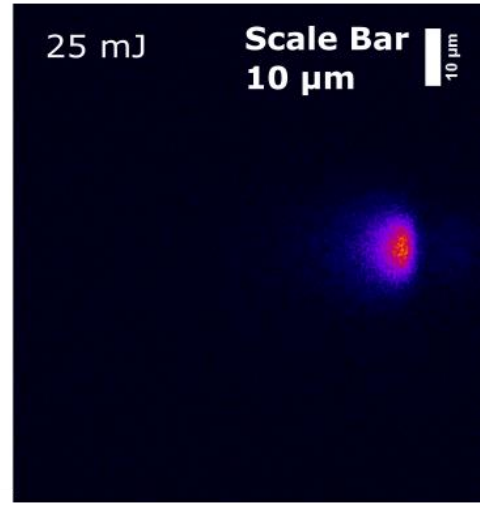
Magnification = 94.   Filter =Si3N4 and Ag

Plasma Side View - Mo

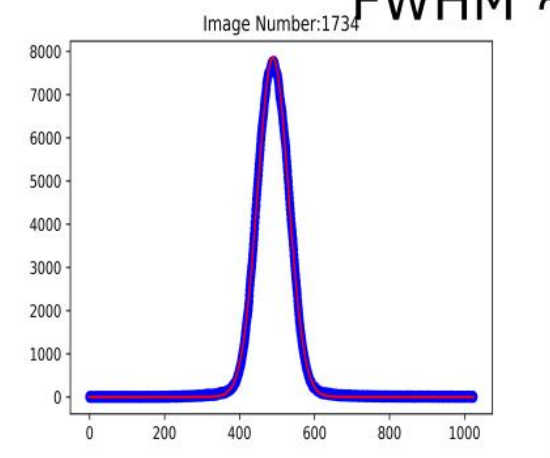
FWHM ~ 5 μm

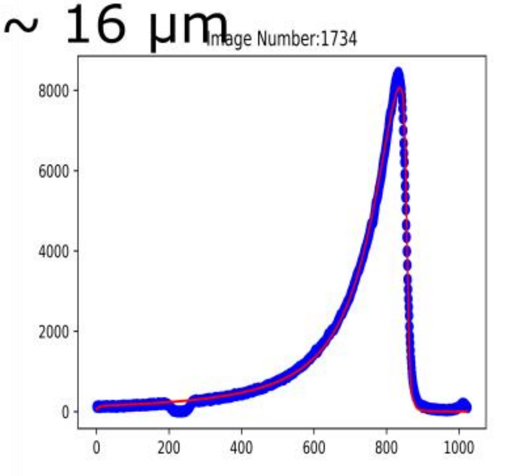


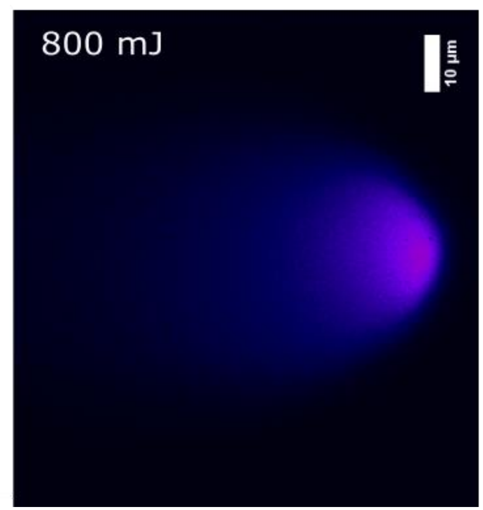




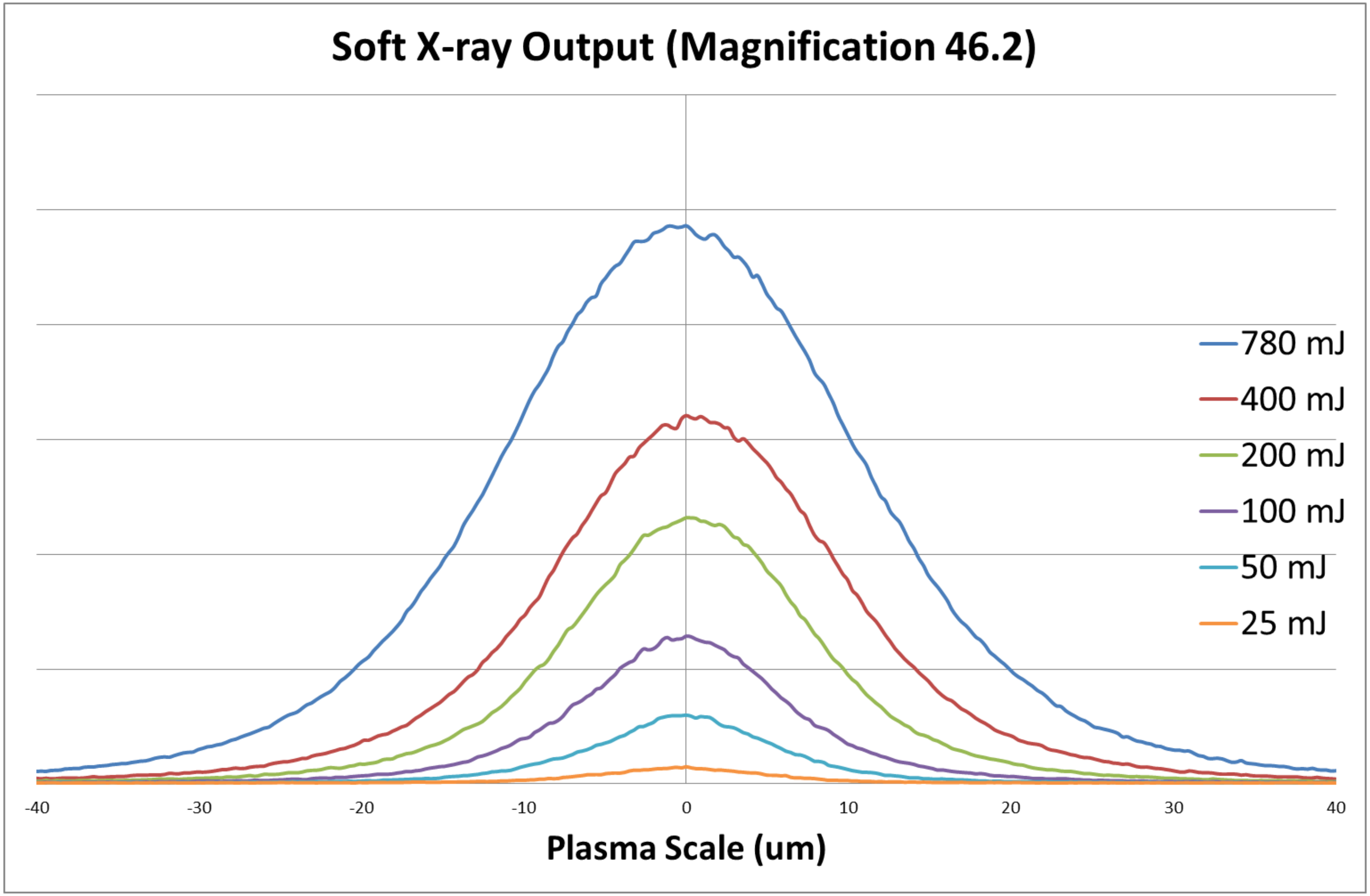
FWHM ~ 16 μm



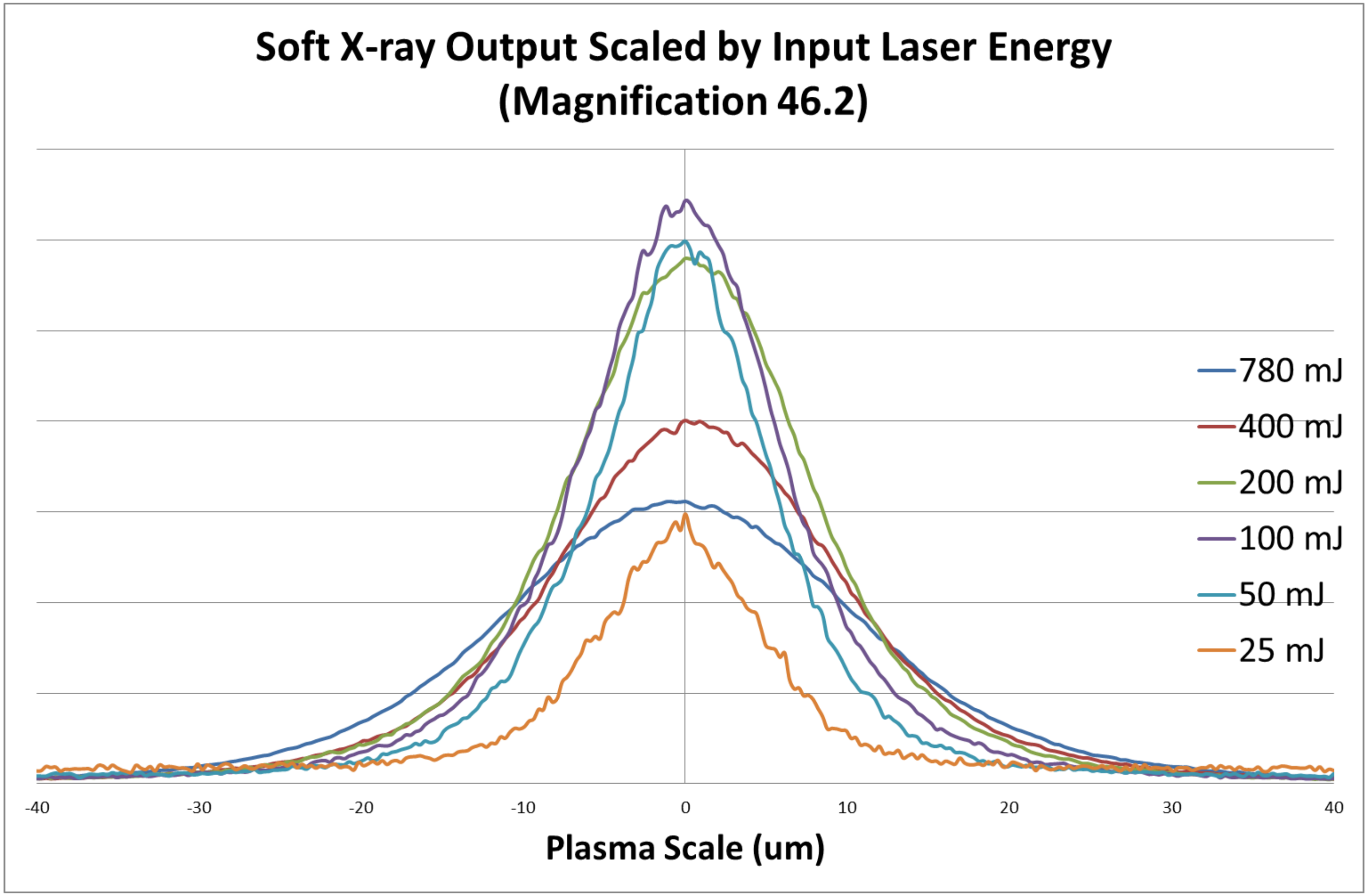




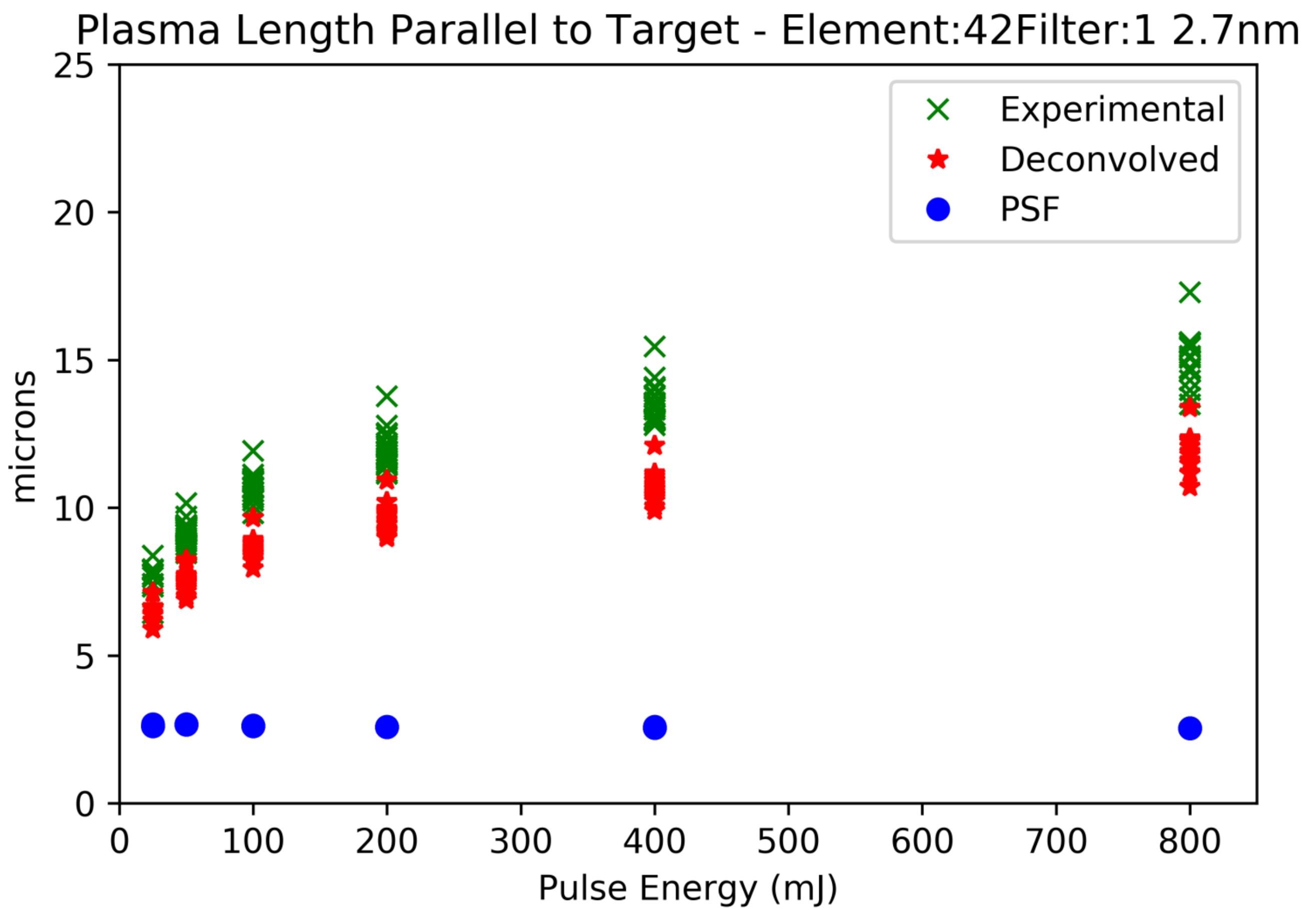
Plasma Front View - Mo



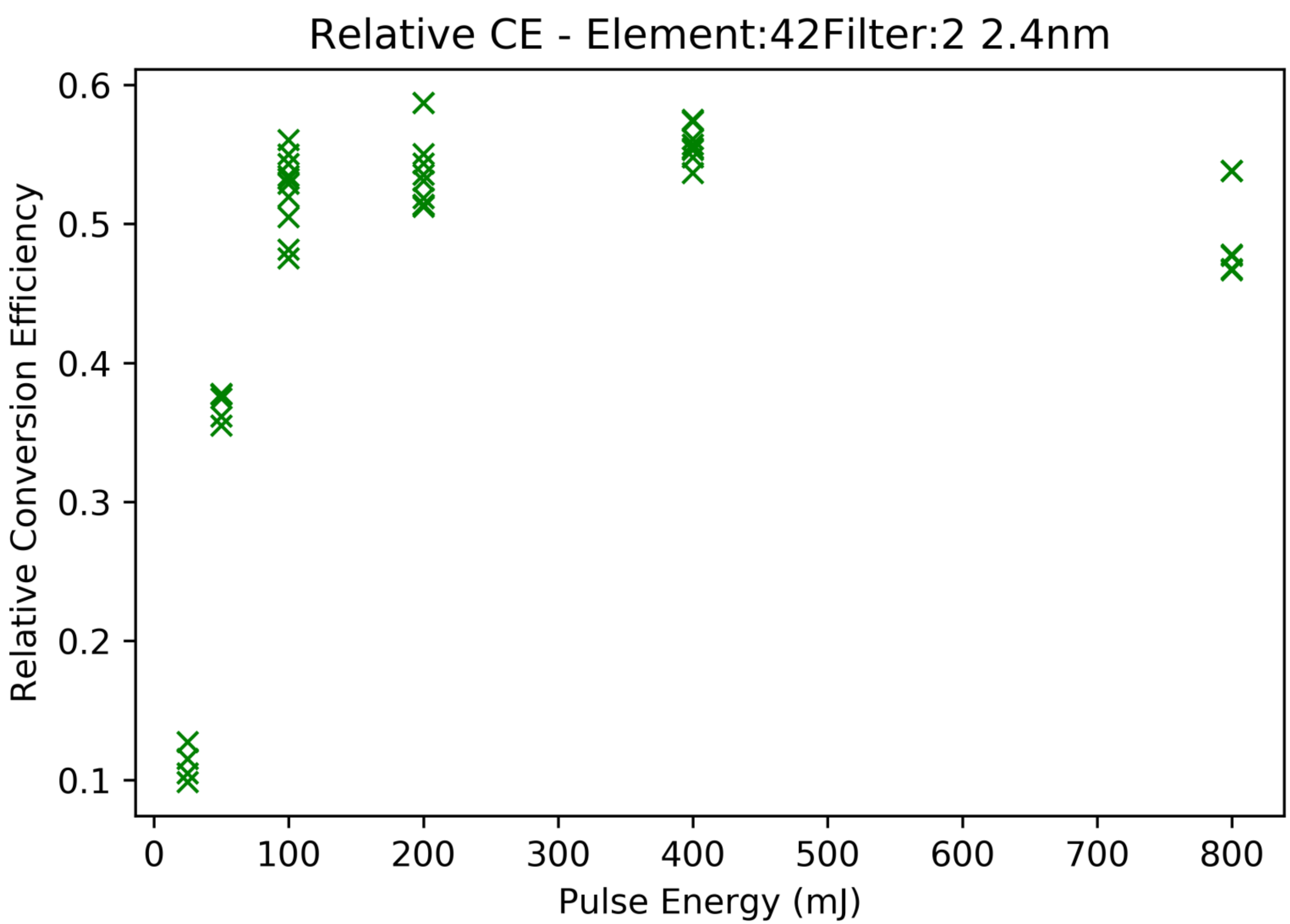
Burning Through



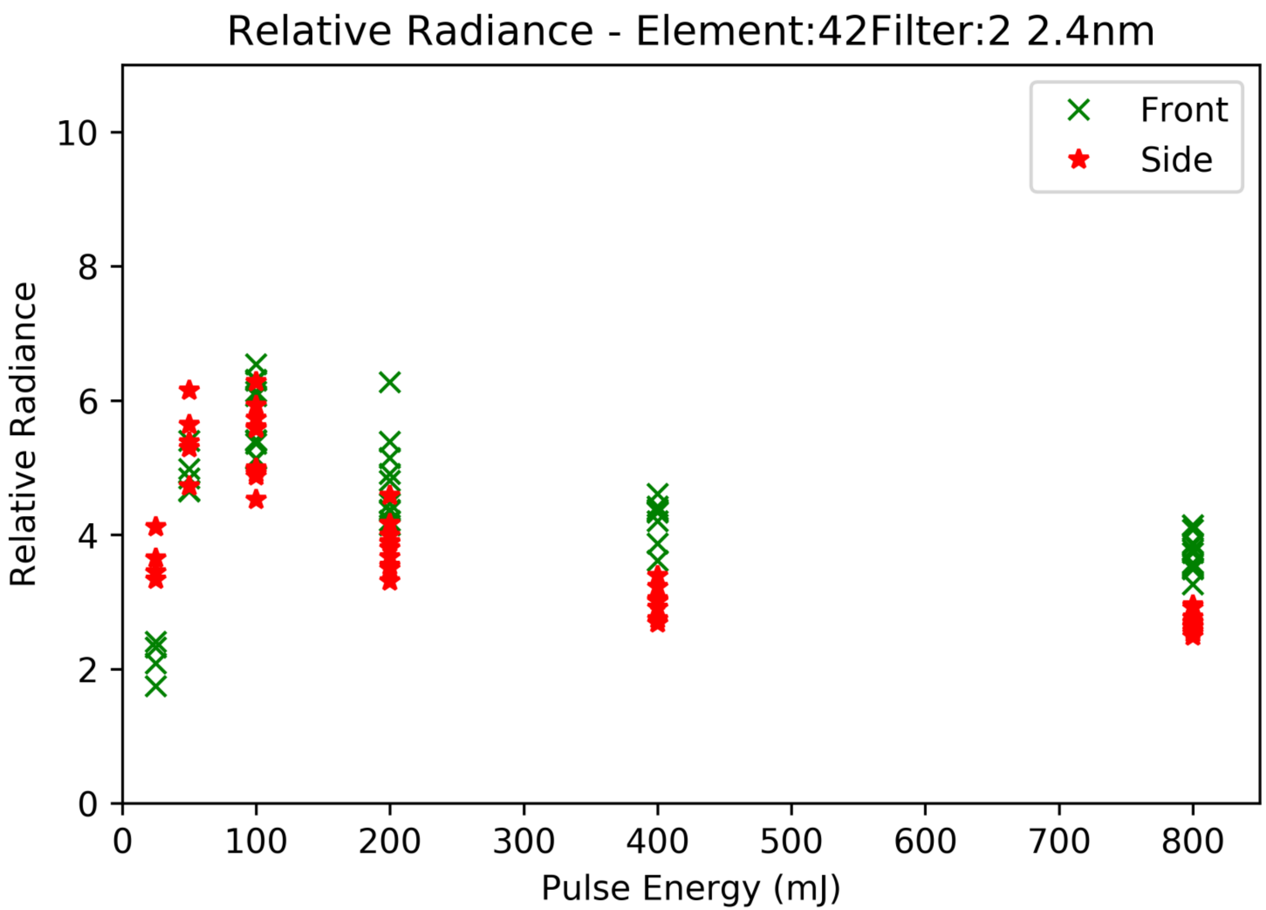
Less Energy = Smaller Plasma



Conversion Efficiency

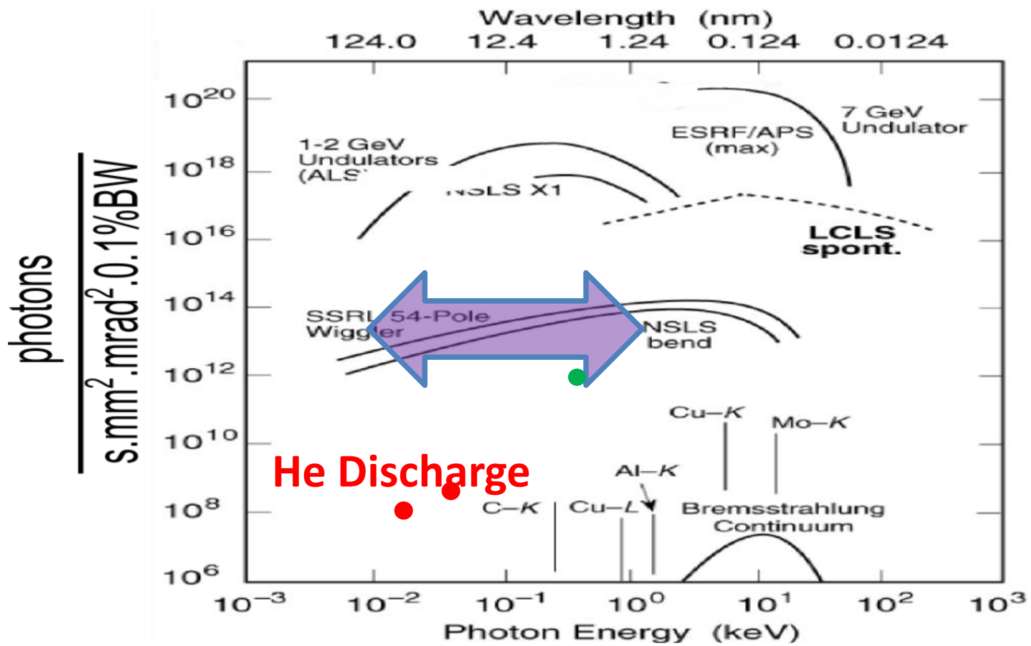


Smaller Not Always Better



Conclusion

- We have demonstrated high CE from sub 10µm plasmas
- Much more space to optimise into



Acknowledgments

Erasmus Mundus
A programme of the European Union

We would like to acknowledge the kind support of

All in the UCD Spec Group,
and the Mechanical and Electronic Workshops, and the
Administrative Staff of UCD School of Physics

EXTATIC - Erasmus Mundus Programme

Thank you for listening